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TROPHIC STATUS OF LAKES IN THALA HILLS, ANTARCTICA —RECORDS FROM THE YEARS 1967–68 AND 1988

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Abstract: Major ions, nutrients and primary production of phytoplankton (PP) investigated in lakes of the Thala Hills, East Antarctica during 1967–68 and 1988 were compared to discuss changes in environmental conditions Lakes Glubokoye and Lagernoye revealed chemical stratification during the former and uniform chemical profiles during the latter period. The contents of phosphates in lake waters during the 1967–68 period reached 750 μg P l^{-1} and those of ammonia 1300 μg N l^{-1}, 1–2 orders of magnitude higher than in the 1988 period and in most of East Antarctic lakes These high contents are explained by higher summer air temperatures which brought about more intensive flushing of the active layer of permafrost with meltwater, and possibly triggered accumulated human impact.

Accordingly, high nutrient levels revealed that in the ice-free water bodies during 1967–68, PP were approaching characteristic levels in nutrient-enriched Antarctic lakes. During 1988 the PP measured in ice-covered lakes were 1–2 orders of magnitude lower and comparable to other Antarctic lakes without animal or human impact. Global warming leading to increased thawing of the permafrost can result in exposure of subsurface organic material to meltwater throughflow which may trigger an increase of trophic level of Antarctic lakes

key words: nutrients, major ions, primary production, human impact, climate warming

Introduction

By far the majority of Antarctic lakes are oligotrophic, primarily because of small nutrient inflows from their catchments, which in turn are fed by Antarctic snowfall usually containing minute amounts of nutrients. This circumstance implies that the small nutrient inflows to the lakes are brought about by extremely reduced development of organisms on the catchments and by low leachout of nutrients from the active ground layer. Exceptions are related to impacts from seal or bird rookeries (HAWES, 1983; PIZARRO *et al.*, 1996) and from scientific stations (HAENDEL and KAUP, 1995). Some recent evidence has shown, however, that fairly high levels of nutrients in lake inflows do occur also in the absence of the latter circumstances (KAUP and BURGESS, 1995). It has been hypothesized that such levels may be the result of release of organic matter (triggered by climatic warming) from permafrost (BURGESS and KAUP, unpublished). In this paper the data obtained from lakes in the Thala Hills, East Antarctica before and after a time interval of 21 years (1967–68 and 1988) are compared and correlated with climatic data in order to evaluate such possibility.

Materials and Methods

The Thala Hills is a coastal ice-free area with more than 60 lakes in Enderby Land, East Antarctica (Fig. 1). The lakes and ponds of the central part of the Thala Hills (67°40′S, 45°51′E) were investigated from February 1967 until March 1968 by E. E. MACNAMARA (1970) and during October–December 1988 by E. KAUP (KAUP and VAIKMÄE, 1996). Lakes Glubokoye and Lagernoye, the two biggest lakes in the central part of the Thala Hills (Fig. 2), were mainly studied and will be treated in detail. The data from two small ponds and a shallow (2 m deep) Lake Melkoye will also be used. All these water bodies are located within 1.5 km from Alasheev Bay.

Both Lakes Glubokoye and Lagernoye have had perennial ice cover (up to 3 m thick in winter) with only narrow discontinous moats in late summer in most years. The area of L. Lagernoye is 5.3 ha and the depth is 10 m; part of Molodezhnaya Station area (where direct human impact has occurred since 1962) with an inflowing from the

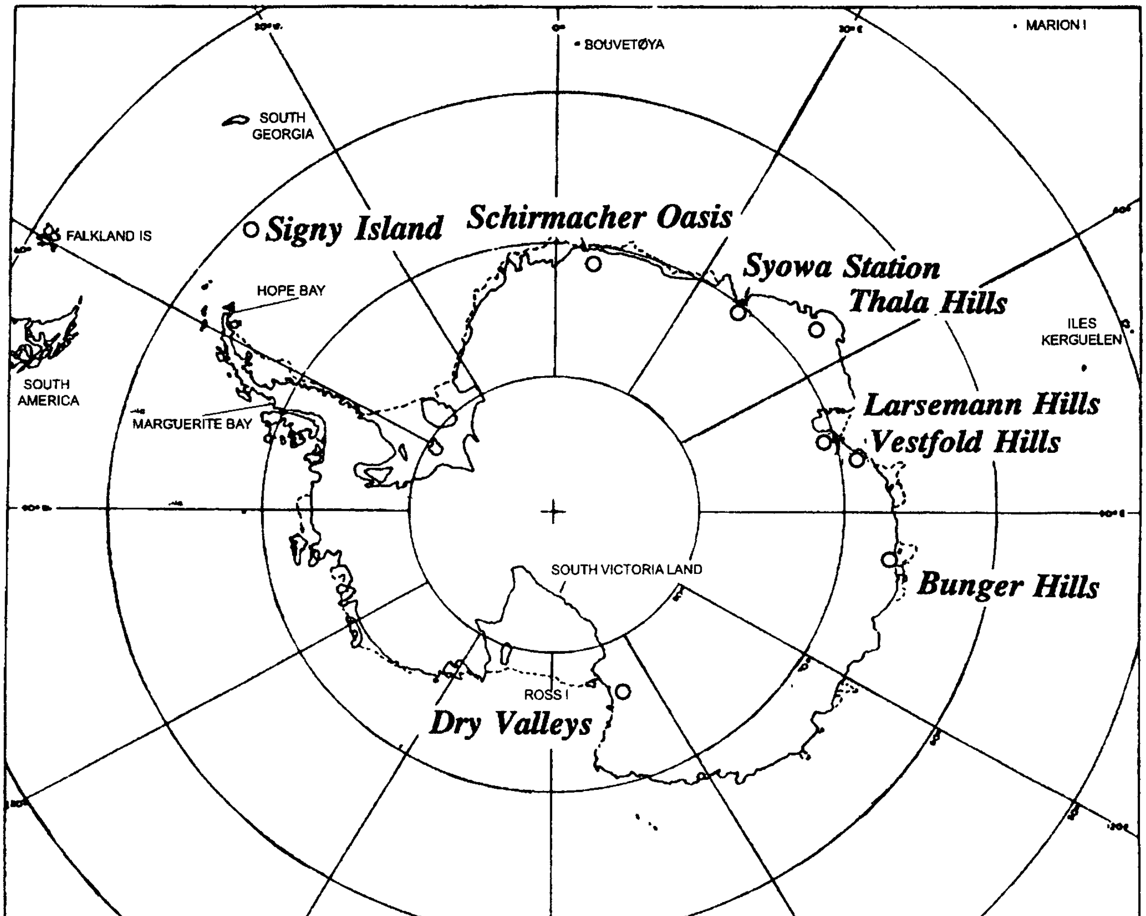

Fig. 1. Antarctic lake regions referred to in the paper.

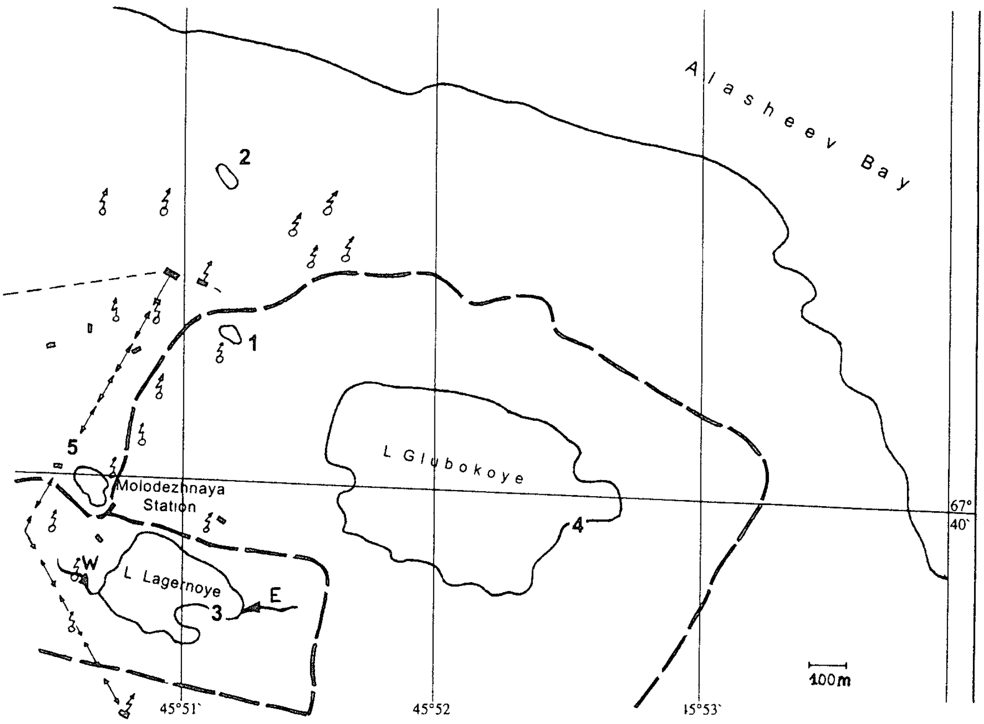

Fig. 2. Investigated lakes in the central part of Thala Hills. 1–Pond N1, 2–Pond N2, 3–Lake Lagernoye, 4–Lake Glubokoye, 5–Lake Melkoye. Dashed lines represent watersheds (After Naval Ministry of the USSR, 1972; air survey of 1968).

west stream is included in the catchment of 40 ha. The lake drains in summer into L. Glubokoye of which the catchment of 230 ha includes but a small part of the station's area (Fig. 2). Every 7–10th summer L. Glubokoye breaks through an ice dam and discharges into Alasheev Bay, decreasing its depth from 36 to 28 m and area from 42 to 28 ha within a few days (ALEKSANDROV and KOZLOVSKYI, 1969; KLOKOV, 1979).

Water samples were obtained through holes drilled into the ice cover with KEMMERER (MACNAMARA) and RUTTNER (KAUP) samplers or directly from the streams into polyethylene bottles (KAUP). Fresh snow samples were collected into plastic bags on the windward side of the station from the surface of old snow cover immediately after precipitation events (KAUP). Sample treatments are described in more detail elsewhere (MACNAMARA, 1970; KAUP and VAIKMÄE, 1996). The former (1967–68) determined pH colorimetrically and the latter (1988) with a glass electrode, chloride by titration (1967–68) and by liquid chromatography (1988), sulphate by the turbidimetric method (1967–68) and by liquid chromatography (1988), respectively. The bicarbonates were titrated potentiometrically to pH 4.3 with HCl. Na and K were measured by flame emission photometry, and Mg and Ca were quantified by Atomic Absorption Spectrophotometry (AAS) (KAUP) while all major cations were measured using AAS by MACNAMARA. The $\delta^{18}O$ (SMOW) was determined on a Finnigan MAT Delta E mass-spectrometer with internal precision of 0.05‰. Both authors determined phosphorus by the ammonium molybdate method, ammonia by Nessler reagent, nitrate and nitrite (not separated by MACNAMARA) by cadmium reduction and 1-naphtyl diamine. Sampling dates for major ions and nutrients were not indicated by

MacNamara (1970). He often reported only average values of several sample analyses. Rates of primary production of phytoplankton (PP) were determined by the light and dark bottle technique with oxygen evolution (MacNamara) and ^{14}C uptake (Kaup).

Results

pH and major ions

Lakes Glubokoye and Lagernoye were slightly acid in 1988 and almost neutral during 1967–68 (Tables 1, 2). During both periods Cl and Na dominated. In 1988 the vertical distributions of major ions (excluding Ca in L. Glubokoye) and total solids

Table 1. pH, major ions (mg l^{-1}) and $\delta^{18}O$ values of water in Lake Glubokoye.

(a) On 14 October 1988 (depth 29.7 m, ice cover 2.45 m).

Depth m	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	Σions	$\delta^{18}O$ ‰
2.5	6.81	4.6	0.6	1.0	0.4	11.5	2.7	4.9	25.7	−20.0
20	6.45	3.9	0.4	1.4	0.6	9.9	2.7	4.6	23.5	−19.4
29	6.44	3.8	0.4	2.1	0.5	9.8	2.7	5.2	24.5	−20.0

(b) During 1967–68 (depths from bottom of ice cover of unreported thickness).

Depth m	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	Σions-HCO_3^-	$\delta^{18}O$ ‰
6	7.1	3	0.3	0.7	0.5	12	4	–	21	–
18	7	4	0.6	0.8	0.6	13	4.8	–	24	–
30	6.8	4	0.6	0 7	0.6	19	10	–	35	–

Table 2. pH, major ions (mg l^{-1}) and $\delta^{18}O$ values of water in Lake Lagernoye.

(a) On 11 October 1988 (depth 10 m, ice cover 2.75 m).

Depth m	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	Σions	$\delta^{18}O$ ‰
3	6.11	4.2	0.4	1.3	0.4	10.6	1.9	4.9	23.7	−19.1
5	6.42	4.0	0.4	1.0	0.4	9.6	1.6	6.1	23.1	−19.3
7	6.67	4.8	0.4	1.0	0.4	9.9	1.6	6.1	24.2	−19.5

(b) During 1967–68 (depths from bottom of ice cover of unreported thickness).

Depth m	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	Σions-HCO_3^-	$\delta^{18}O$ %
0.3	6.7	2	1	0.2	0.3	20	5	–	28.5	–
4.2	7	3	1	0.4	0.4	35	3	–	42.2	–
7.2	7	7	1	0.4	0.4	45	1.2	–	54.2	–

(Σ ions) were uniform in both lakes as also evidenced by unity $\delta^{18}O$ values. The content of total solids in both lakes was between 23–26 mg l^{-1}, but that in L. Melkoye reached 164 mg l^{-1} under 1.65 m thick ice cover. During 1967–68 Cl content increased markedly with depth in both big lakes; SO_4 content increased with depth in L. Glubokoye but decreased in L. Lagernoye. Na content increased with depth in L. Lagernoye. As a result of these changes the content of total solids (without HCO_3) revealed prominent increases with depth in 1967–68, reaching 35 and 54 mg l^{-1} at the bottoms of Lakes Glubokoye and Lagernoye, respectively. In the open ponds N1 and N2 total solids (without HCO_3) varied between 29–39 mg l^{-1}.

Nutrients

The average content of phosphates was the highest (20 μg P l^{-1}) in 1967/68 summer precipitation samples which were also higher than the previous winter (Table 3). During November–December 1988 phosphate in precipitation samples was 8.4 μg P l^{-1} on average. The average ammonia content was found to be 1800 μg N l^{-1} during 1967–68, which was an order of magnitude higher than that of 1988. Although nitrates and nitrites were not detected during the former, they were (on average) 28.3 and 1.4 μg N l^{-1}, respectively, during the latter period (Table 3).

At the end of December 1988 the levels of phosphates in the stream draining the station's area were 25–250% higher than those in a stream draining a snowfield in natural conditions. The levels of inorganic nitrogen (NO_2-N, NO_3-N and NH_4-N), especially in the latter case, were also much lower (Table 4).

The vertical distributions of the low levels of nutrients (phosphates up to 7 μg P l^{-1}) were mostly uniform in 1988 both in Lakes Glubokoye and Lagernoye (Tables 5, 6). Higher levels of ammonia (up to 260 μg N l^{-1}) were observed in L. Glubokoye during the two first samplings in October. The nutrient levels in L. Melkoye were similar to those in Lakes Glubokoye and Lagernoye. During 1967–68 the levels of phosphates and ammonia in L. Glubokoye varied from 65 to 460 μg P l^{-1} and 620 to

Table 3 Nutrients (μg l^{-1}) in average in precipitation samples

Period	PO_4-P	NO_3-N	NO_2-N	NH_4-N
1988 Nov.–Dec. 7 samples	8 4	28.3	1 4	190
1967 winter 10 samples	13	0	0	1700
1967/68 summer 5 samples	20	0	0	1800

Table 4. Nutrients (μg l^{-1}) in the stream draining the station's territory and entering L Lagernoye from the west and in the stream draining a snowfield and entering L. Lagernoye from the east

Direction	Date	PO_4-P	NO_3-N	NO_2-N	NH_4-N
West	23 12 88	10	80	3.0	1200
West	26 12 88	13	44	2.0	230
West	30.12.88	20	130	1 5	170
East	30 12.88	8	48	0 5	17

Table 5. Nutrients ($\mu g\,l^{-1}$) in Lake Glubokoye.

(a) During October–December 1988 (6 samplings).

Depth, m	PO_4-P	NO_3-N	NO_2-N	NH_4-N
5	1–6	1–5	0.7–3.5	12–260
20	1–5	1–3	1.2–3.5	20–215
29	1–6	2–6	0.5–3.0	5–200

(b) During 1967–68 (depths from bottom of ice cover of unreported thickness).

Depth, m	PO_4-P	NO_3-N + NO_2-N	NH_4-N
6	65	0	620
18	65	0	620
30	460	0	1320

Table 6. Nutrients ($\mu g\,l^{-1}$) in Lake Lagernoye.

(a) During October–December 1988 (6 samplings).

Depth, m	PO_4-P	NO_3-N	NO_2-N	NH_4-N
3	1–5	2–5	1.0–2.8	10–54
5	2–5	2–3	1.0–3.3	5–32
7	2–7	1–3	1.0–4.3	5–35

(b) During 1967–68 (depths from bottom of ice cover of unreported thickness).

Depth, m	PO_4-P	NO_3-N + NO_2-N	NH_4-N
0.3	390	0	930
4.2	310	0	740
7 2	294	35	620

1320 $\mu g\,N\,l^{-1}$, respectively, increasing with depth (Table 5), while those of phosphate and ammonia in L. Lagernoye ranged from 294 to 390 $\mu g\,P\,l^{-1}$ and from 620 to 930 $\mu g N\,l^{-1}$, respectively, decreasing with depth (Table 6). Nitrates + nitrites were observed only near the bottom of L. Lagernoye (35 $\mu g N\,l^{-1}$ level, Tables 5, 6). The levels of phosphates, nitrates + nitrites and ammonia in ponds N1 and N2 were 130–750 $\mu g\,P\,l^{-1}$, 0–180 $\mu g\,N\,l^{-1}$ and 390–1240 $\mu g\,N\,l^{-1}$, respectively.

Primary productivity

The oxygen production by phytoplankton during November–January 1967/68 was detected only at 0.3 m depth under the open water surface of ponds N1 and N2, and of the moat of L. Glubokoye. Primary production values estimated from oxygen production were between 140 and 371 $mg\,C\,m^{-3}\,day^{-1}$. The PP values during October–December 1988 were between 0.2–4.8 $mg\,C\,m^{-3}\,day^{-1}$ in L. Glubokoye,

Table 7 Primary productivity of phytoplankton (PP, $mg\,C\,m^{-3}\,day^{-1}$) during October–December 1988

Lake	Depth, m	Number of tests	Temp °C	PP
Glubokoye	3	5	0.2–3.9	0 6–2.4
	20	5	3 8–4 3	0.5–1.7
	29	5	4.1–4.4	0 2–4.8
Lagernoye	3	5	0.2–4.0	1 2–8.6
	5	5	1 4–4 1	3 4–11.8
	7	5	2.5–4.0	3 6–11.1
Melkoye	1.8	3	5.6–6 0	3.0–57.0

1.2–11.8 $mg\,C\,m^{-3}\,day^{-1}$ in L. Lagernoye and 3.0–57.0 $mg\,C\,m^{-3}\,day^{-1}$ near the bottom of L. Melkoye (Table 7). All these measurements were performed under the ice cover.

Discussion

The October–December (end of winter–early summer) 1988 data on major ions, total solids and nutrients showed that Lakes Glubokoye and Lagernoye were chemically unstratified and uniform $\delta^{18}O$ values indicate that the waters had circulated since inflow. In concert with uniform nutrient profiles in these lakes further data revealed (KAUP and VAIKMÄE, 1996; KAUP, unpubl.) that although the lakes were stratified by temperature and dissolved oxygen, no anaerobic conditions appeared even at 0.2 m above the bottom and as early as mid-October. The data of 1967–68 on major ions and total solids show chemical stratifications in Lakes Glubokoye and Lagernoye. The vertical differences of water density brought about by such stratifications imply stability of the water column under ice cover. This stability is not likely to be destroyed by the changes in water temperature within 0–4.5°C (HUTCHINSON, 1957) observed in these lakes. This suggests that both Lakes Glubokoye and Lagernoye possessed temporary meromixis with possibly anaerobic hypolimnion during sampling in 1967–68. The increases of phosphates and ammonia with depth in L. Glubokoye support the latter suggestion while the opposite changes in L. Lagernoye may in addition reflect the impact of inflowing water with lower total solids and higher nutrient contents than those in the lake. Even though the nutrient content in precipitation was found to be higher in 1967–68 than in 1988 this cannot account for 1–2 orders of magnitude higher nutrient contents, especially of phosphates, in the lakes during 1967–68. The nutrient levels in 1967–68 were generally more than an order of magnitude higher than those found in other freshwater lakes of East Antarctica (FUKUI *et al.*, 1986; GARDNER *et al.*, 1984; HAENDEL and KAUP, 1995). In the Larsemann Hills, the average water column content of phosphates of 11 lakes was found to be 25 $\mu g\,P\,l^{-1}$ (the mean value, with the range 7–52 $\mu g\,P\,l^{-1}$), and was explained by leachout from the active layer (KAUP and BURGESS, 1995).

Large differences of nutrient contents in Lakes Glubokoye and Lagernoye found between 1967–68 and 1988 may cast doubt on their reliability. As noted above, similar

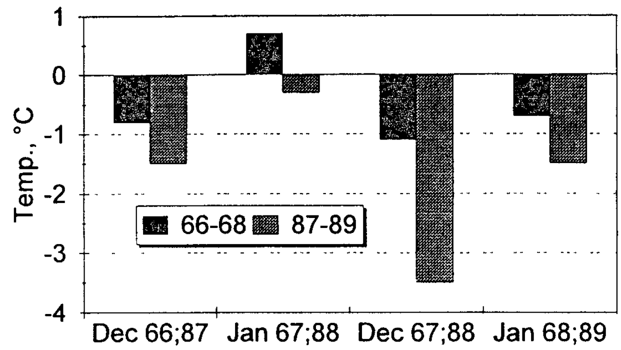

FIG. 3. Average air temperature at Molodezhnaya Station in December–January during 1966–68 and 1987–89.

analytical methods were used. Second, both authors obtained similar low-level phosphorus data from precipitation (Table 3) while the ammonia content varies with wide range in Antarctic precipitation, particularly in the Thala Hills where the range was 12–380 $\mu g\,N\,l^{-1}$ (KAUP and VAIKMÄE, 1996). Third, using the same methods KAUP has measured widely varying nutrient contents in Antarctic lakes (HAENDEL and KAUP, 1995; KAUP *et al.*, 1993). Hence the nutrient results are likely reliable. MACNAMARA (1970) noted that phosphates and nitrogen compounds in 1967–68 samples were in some cases related to contamination by Adélie penguins, South Polar skuas and human impact. While these contaminations were not specified it is likely that the latter one was more pronounced in L. Lagernoye because of the position of a major part of its catchment on the station's area.

The much higher content of nutrients during December 1988 in the stream draining of the station's area and entering L. Lagernoye from the west compared with the stream draining a natural snowfield and entering the lake from the east (Table 4) is in accordance with the latter statement. However, the meltwater inflow during December 1988 must have been among the smallest since 1963 because the average December air temperature of -3.5°C in this month, which was also 2.4°C lower than in December 1967, was the lowest recorded during 1963–89 (DOLGIN and PETROV, 1977; KOROTKEVICH, 1975–90). Further, the average air temperature of -0.9°C for December–January of the previous summer 1987/88 was 0.85°C lower than that for December–January 1966/67 (Fig. 3). Such air temperature differences, particularly near 0°C, are able to bring about very substantial differences in the production of meltwater, in the depth of thawed active layer of permafrost and thus in the amount of nutrients leached out by the former from the latter. The spring contents of the nutrients in Antarctic lakes also largely depend on the inflow during the previous summer. Therefore the observed differences in summer air temperatures may at least partly account for the observed different nutrient contents in Lakes Glubokoye and Lagernoye during 1967–68 and 1988.

Evidence obtained from the Larsemann Hills, Antarctica suggests that ground water can also be a major contributor of nutrients to the lake ecosystem (BURGESS and KAUP, unpubl.). In addition, in the Larsemann Hills extensive vegetation beds (mosses, cyanobacterial mats) have been found to exist during the warmer climates of the past (BURGESS *et al.*, 1994). Speculating about the role of frozen organic material contained in permafrost, global warming may lead to increased melting of the permafrost and the resulting exposure of subsurface organic material to meltwater throughflow may trigger an increase of trophic levels of Antarctic lakes.

On the other hand, the human impact was probably stronger before and during 1967–68 when sewage water from laundry, sauna and kitchen was released onto the catchment of L. Lagernoye. In warmer summers, organic and nutrient matter of human origin which has accumulated in the active layer during winters and cold summers is readily leached out by runoff. Construction and transportation activities in Antarctic oases were shown to have drastically changed the pattern, quality and quantity of drainage (BURGESS *et al.*, 1992).

The oxygen method used during 1967–68 was not sensitive enough to detect PP under the ice cover of lakes. A few values measured in open ponds and in the moat of L. Glubokoye, when converted to carbon fixation, ranged from 140 to 371 mg C m^{-3} day^{-1}. This range is similar to the PP of 300–700 mg C m^{-3} day^{-1} in open water in eutrophic Heywood Lake, Signy Island, which receives nutrients from seal wallows (ELLIS-EVANS, 1981b). The 1 to 2 order of magnitude lower values of PP measured during October–December 1988 under ice cover (Table 7) are consistent with low nutrient levels and comparable to PP measured in several uncontaminated Antarctic lakes. These are up to 20 mg C m^{-3} day^{-1} in Moss Lake, Signy Island (ELLIS-EVANS, 1981a), 4–65 mg C m^{-3} day^{-1} in Watts Lake, Vestfold Hills (HEATH, 1988), 1–19 mg C m^{-3} day^{-1} in several freshwater lakes of Bunger Hills (KAUP *et al.*, 1993) and 0.1–7 mg C m^{-3} day^{-1} in the lakes of Schirmacher and Untersee Oases (HAENDEL and KAUP, 1995).

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